TNO-report
TM-97-B024

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Remotely controlled flying aided by a head-slaved camera and HMD

TNO Human Factors
Research Institute

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titel:	Afstand bestuurd vliegen ondersteund door een hoofd-gekoppelde camera en HMD
auteurs:	Dr. S.C. de Vries en dr. P. Padmos
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Onbemande vliegtuigen (Unmanned Aerial Vehicles, UAV's) zijn al enkele tientallen jaren in gebruik bij diverse strijdmachten in de wereld. De laatste tijd neemt hun belang aanzienlijk toe. Zowel in de Golfoorlog als in het voormalige Joegoslavië zijn ze in ruime mate ingezet. Er bestaat inmiddels een groot scala aan types, van zeer grote, hoogvliegende radarverkenners tot kleine laagvliegende vliegtuigjes, helikoptertjes en visueel bestuurde raketten. Hoewel het vliegen vaak geautomatiseerd is, zijn er situaties waarin een menselijke operator de besturing overneemt. In het geval dat er een videocamera aan boord is en deze sensor van de UAV handmatig bestuurbaar is, kan er onduidelijkheid ontstaan over de relatie tussen vlieg- en kijkrichting. Eén van de mogelijke oplossingen is de richting van de UAV-sensoren te koppelen aan de hoofdbewegingen van de operator, waardoor een duidelijker referentiekader ontstaat. De sensorbeelden worden hierbij recht voor de ogen van de operator op een Head Mounted Display (HMD) afgebeeld. Alvorens te testen of deze methode voordelen biedt boven handmatige besturing is het zaak te bestuderen welke factoren de stuurprestatie beïnvloeden bij een dergelijke ondersteuning van de stuurtaak, zodat hoofdgekoppelde camerasturing optimaal afgezet kan worden tegen handbesturing. Een aantal van deze factoren is in dit onderzoek onderzocht. Deze factoren zijn verder ook van belang voor bestuurders die wèl in hun voertuig zitten en ondersteund door visuele hulpmiddelen dit voertuig besturen (gemedieerd zicht). De Apache AH-64 helikopter beschikt bijvoorbeeld over een op de neus bevestigde en hoofdgestuurde infra-rood sensor en helderheidsversterker. De metingen leveren verder informatie die voor simulatoren in het algemeen van belang is.
Het onderzoek werd in de TNO-TM vliegsimulator uitgevoerd, waar een gesimuleerde UAV-vlucht door een bochtig en in hoogte variërend geuldal werd uitgevoerd. De taak van de proefpersonen was een slalomparcours gemarkeerd door gekleurde bomen zo goed mogelijk af te leggen, waarbij een vaste afstand van de bomen en een vaste hoogte boven de grond moest worden aangehouden.
In het experiment werd gekeken naar de factoren beeldhoek, camera-vertraging, monoculaire vs. stereoscopische presentatie en HMD-type. Om de beeldhoek te kunnen variëren werd een HMD nagebootst door een in grootte instelbaar (gesimuleerd) venster kijkrichting-gestuurd over de geprojecteerde simulatorbeelden te laten bewegen. Eén van de beeldgroottes die op deze manier werd aangeboden correspondeerde met de grootte van de eveneens in dit experiment gebruikte Virtual IO i-glasses HMD waardoor een vergelijking mogelijk werd.
De resultaten laten zien dat het gebruik van de gesimuleerde HMD een significant betere stuurprestatie oplevert dan gebruik van de echte HMD; dit kon echter niet toegerekend worden aan verschillen in resolutie. De prestatie bij een beeldhoek van 17° is significant lager dan bij 34 of 57°. Een cameravertraging van 50 ms, typisch voor de mechanische vertraging die bij servosystemen optreedt, had een significante invloed op de stuurnauwkeurigheid. En als laatste: de monoculaire and stereoscopische presentatiewijzen leidden niet tot verschillende prestaties.

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Authors:	Dr. S.C. de Vries and Dr. P. Padmos
Institute:	TNO Human Factors Research Institute Group: Skilled Behaviour
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SUMMARY

Military use of Unmanned Aerial Vehicles (UAVs) is gaining importance. Video cameras in these devices are often operated with joysticks and their image is displayed on a CRT. In this experiment, the simulated camera of a simulated UAV was slaved to the operator's head movements and displayed using a Helmet Mounted Display (HMD). The task involved manoeuvring a UAV along a winding course marked by trees. The influence of several parameters of the set-up (HMD optics, Field of View (FOV), image lag, monocular vs. stereoscopic presentation) on a set of flight handling characteristics was assessed. To enable variation of FOV and to study the effect of the HMD optics, a simulated HMD image consisting of a head slaved window (with variable FOV), was projected on a screen. One of the FOVs, generated in this way, corresponded with the FOV of the real HMD, enabling a comparison. The results show that the simulated HMD yields a significantly better performance than the real HMD. Performance with a FOV of 17° is significantly lower than with 34 or 57°. An image lag of 50 ms, typical of pan-and-tilt servo motor systems, has a small but significant influence on steering accuracy. Monocular and stereoscopic presentation did not result in significant performance differences.

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TNO Technische Menskunde
Soesterberg

Afstand bestuurd vliegen ondersteund door een hoofd-gekoppelde camera en HMD

S.C. de Vries en P. Padmos

SAMENVATTING

De militaire toepassing van onbemande vliegtuigen (UAV's) wint aan belangstelling. Beeldvormende sensoren in deze toestellen worden dikwijls handmatig bediend door middel van joysticks waarbij hun beeld wordt weergegeven op een monitor. Deze wijze van aansturing zou een negatieve invloed kunnen hebben op het situationeel bewustzijn van de operator: de relatie tussen kijkrichting en vliegrichting kan onduidelijk worden. In dit experiment werd een gesimuleerde camera van een gesimuleerde UAV bestuurd door de hoofdbewegingen van de bestuurder, terwijl de beelden werden getoond door middel van een Head Mounted Display (HMD), waardoor een meer ecologische koppeling tussen sturing van sensor en waarneming van het corresponderend beeld ontstaat.
De opdracht van de bestuurder was het zo goed mogelijk manoeuvreren van een UAV langs een bochtig en heuvelachtig parcours gemarkeerd door bomen.
De invloed van een aantal parameters van de opstelling (HMD optiek, beeldgrootte, beeldvertraging, monoculaire of stereoscopische presentatie) op een verzameling prestatie- en gedragskarakteristieken werd bestudeerd. Om de beeldgrootte te kunnen variëren en het effect van de HMD-optiek te kunnen bestuderen werd een HMD gesimuleerd door over de in een bolprojectie weergegeven scène een computergegenereerd en hoofdgekoppeld venster te leggen. Eén van de beeldgroottes die op deze manier werd aangeboden correspondeerde met de beeldgrootte van de echte HMD die ook in het experiment werd gebruikt. Hierdoor werd een vergelijking mogelijk.
De resultaten laten zien dat het gebruik van de gesimuleerde HMD een significant betere stuurprestatie oplevert dan gebruik van de echte HMD; dit kon echter niet toegerekend worden aan verschillen in resolutie. Eén hypothese is dat de in het eerste geval zichtbare randen van het projectiescherm en de overgangen tussen de beeldkanalen van het beeldsysteem voertuigreferenties vormen die door de proefpersonen zijn gebruikt om hun situationeel bewustzijn te vergroten.
De prestatie bij een beeldhoek van 17° is significant lager dan bij 34 of 57°. Een cameravertraging van 50 ms, typisch voor de mechanische vertraging die bij servosystemen optreedt, had een kleine maar significante invloed op de stuurnauwkeurigheid. De monoculaire and stereoscopische presentatie leidden niet tot verschillende prestaties.

1 INTRODUCTION

In flying some Unmanned Aerial Vehicle (UAV) systems, the remote operator's view of the ambient world is provided by one or more cameras on the vehicle and one or more monitors at the control station. In order to provide a large visual field, while restricting the required transmission capacity from vehicle to operator, a head tracked pan-and-tilt camera on the UAV combined with a Head Mounted Display (HMD) is a potentially attractive solution. Head-tracked control of the camera's viewing direction is more attractive than joystick control because, firstly, the operator's hands remain free and, secondly, the operator presumably knows intuitively and precisely in what direction with respect to himself and the UAV. Before comparing head-tracked control and joystick control it makes sense to determine how several parameters of the system affect operator performance, so that the comparison can be made for a reasonably optimized set-up. Additionally, the same factors that affect performance in remote control will also effect pilots who are provided with sensor information in the same way as in the Apache and Cobra helicopters, where a HMD is combined with a head tracked pan-and-tilt infra-red and image-intensifier sensor. The goal of the current research was to examine several of these factors.

The present report is aimed at the question of the required instantaneous visual field size for a HMD-camera system, for adequately performing a nap-of-the-earth (NOE) flight on a winding course. In the same experiment we studied the performance effects of stereoscopic vs. monocular image presentation, and of the introduction of an image lag due to delays in the camera's servo-motor system.

The instantaneous field size is a technically important parameter in the design of a HMD-camera system, because it is related to parameters such as spatial resolution, magnification, and required transmission capacity. Operationally it is important because with larger instantaneous field sizes less head motion is required to anticipate the course of the path to be flown, and generally there is a more accurate perception of the vehicle's motion (Padmos, 1995; Warren, Blackwell, Kurtz, Hatsopoulos & Kalisk, 1991).

In principle, a stereo image requires two cameras, which doubles the required transmission capacity. However, it enables better depth perception than a image containing only monocular information, albeit that its advantage is generally small compared with monocular depth cues at distances above 15 m (Padmos, 1992, 1995). One of the questions in this experiment was whether stereopsis is useful in low-flying tasks when distances in this range are present.

Image delays due to camera inertia are unavoidable. In practice delays can be restricted to 50 ms, with a sophisticated, powerful, tracking system (Sharkey & Murray, 1993). It was reported that slaving system imperfections (time constant 0.5 s) in a helicopter simulation seriously constrain the pilot from making fast head movements and increased the time to estimate a location of a point on the flying path (Grunwald, Kohn & Merhav, 1991). In an object handling task for subjects wearing a HMD, Kawara, Ohmi and Yoshizawa (1996) found that version eye movements and accommodative response speed were delayed in the course of 40 minute sessions with image lags of 0.3 and 0.5 s, which was interpreted as increased visual fatigue. This is another indication for the load introduced by large image

lags. It is of interest to know to which extent performance and load are influenced by a realistic image lag.

2 METHODS

2.1 Simulator and image presentation

The simulator consists of an Evans and Sutherland ESIG 2000® image generator with three channels, using as a display system either a HMD (Virtual IO i-glasses®) or a dome projection system (Seos HiView S-600®). A simple dynamic model was used for the UAV. It had a constant cruising speed of 25 km/h, and its yaw angle speed (-24 to +24 °/s) and vertical speed (-1 to +1 m/s) were controlled by a joystick (Logitech Wingman®). The joystick's signals were fed to a first order low-pass filter with a time constant of 2 s, which served as the dynamic model of the UAV. The subject was seated in the centre of a spherical screen, on which the scene could be presented. He wore a helmet on which the sensor of a Polhelmus Fastrack® magnetic head tracking system was mounted. Yaw and pitch of the head motion were fed into the image generator.

We tested the effects of eight different viewing conditions on flying performance, head motion and subjective task difficulty. Among these conditions were two with a real HMD, all other conditions employed a simulated HMD. In one real HMD condition the outside world scene was presented stereoscopically, and in the other the image was monoscopic, but presented dichoptically to both eyes (diagonal field 28°). The additional viewing conditions were designed as HMD simulations, set up to manipulate optical presentation of the head slaved area of interest, field size and image lag. In one of those simulations, the HMD was replaced by tubes mounted on the head, in which an aperture limited the instantaneous field to about the same size as the HMD (see Figure 1). The subjects could scan the outside world scene projected on a screen, with dimensions 151° H × 45° V. In three conditions the subject looked had a direct view on the dome projection. In these cases, the instantaneous field of view was restricted by a window which slaved the subject's head motion. Diagonal field sizes were 17°, 34°, and 57°, respectively. The (estimated) delay of the window motion compared to the head motion (70 ms) was determined by the head tracker's update rate and the image generator's image delay. The conditions with field size 17° and 57° were also presented with an additional lag on the image content of 50 ms.

a

b

c

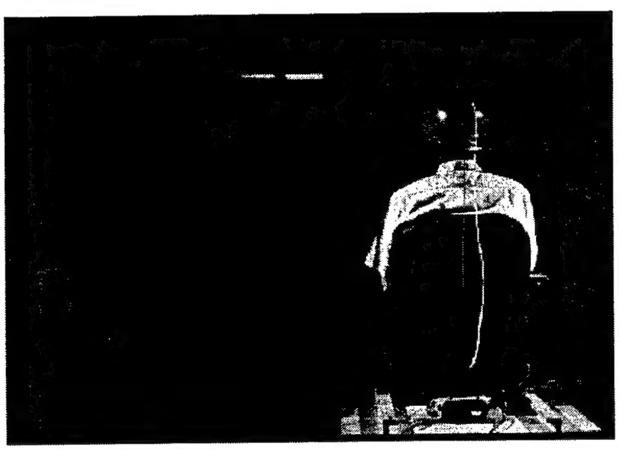

Fig. 1 Examples of viewing conditions. **a:** The virtual IO i-glasses HMD; **b:** HMD simulation by means of FOV restricting spectacles; **c:** HMD simulation by means of a head-tracked window.

2.2 Database

The simulation database contained 32 different routes. They consisted of successive curved segments, with right and left curves, marked with trees of height 8.5 m, maximal diameter 2 m, and a inter-tree distance of 12 m. The trees were alternately grouped in red and green rows, red trees on the right side of the route, green trees on the left side. The terrain was textured, and sloping. The route was in the middle of a canyon, limited on both sides by a dike, at 20 m from the centre of the course.

The shape of the path, including the slopes, was constructed by means of a path generator, consisting of the UAV dynamic model steered by time-varying signals corresponding to yaw angle speed and vertical speed. The signals had a block shape which had passed a integrating filter with a time constant of 2 s. The heights of the signal blocks were drawn randomly from evenly distributed populations, with maxima equal to 80% of maximum UAV's yaw angle speed and vertical speed, respectively. This procedure guaranteed that it was physically possible to fly the route, whilst it was necessary to make head movements to determine the path curvature, even with the largest instantaneous field size. The signal block lengths were drawn randomly from an evenly distributed population, with the constraint that the path's direction should not cross itself. Each route started with a straight horizontal part of 75 m. The length of each route was 1.7 km.

2.3 Subjects, task, and training

Eight paid subjects, male university students of age 18-25, participated. They had normal visual acuity, stereo acuity and colour vision. Subjects received a general instruction on aim and design of the experiment, followed by three training sessions. The subjects' task was to follow routes marked with trees, trying to keep a lateral distance of 3 m to the trees, and a height of 3 m above the ground. The red trees were to be kept on their right side, the green trees on their left side. The flying time of each route was about 4 minutes.

In the training session subjects followed three different consecutive routes while they received both sound feedback and verbal feedback on their performance. The continuous sound feedback consisted of tones provided by speakers to the left and the right of the subject, indicating horizontal and vertical deviation from the target path, in steps of 0.5 m. Apart from the sounds, subjects received verbal feedback on their performance and their looking and steering strategy.

2.4 Dependent variables

The dependent variables consisted of flying performance measures, head motion attributes, and subjective difficulty scores.

Flying performance. The following measures were derived from comparison of the UAV's position (sampled with 10 Hz) with the target route (horizontal and vertical):

DISTH, DISTV	the lateral orthogonal error and the height error, relative to the target route (m)
MDISTH, MDISTV	the mean over one run of DISTH and DISTV (m)
SDH, SDV	the standard deviation over one run of DISTH and DISTV (m)
SDSPEEDH, SDSPEEDV	the standard deviation over one run of lateral and vertical error speed (m/s).

Head motion attributes. From the head yaw and pitch (sampled with 10 Hz) the following measures were derived:

MYAW, MPITCH	the means over one run of yaw and pitch (°)
SDYAW, SDPITCH	the standard deviation over one run of yaw and pitch (°)
STDYSP, SDTPSP	the standard deviation over one run of yaw speed and pitch speed (°/s)
TOTKOPMO, STDKOPMO	mean, resp. standard deviation over one run of the total speed vector magnitude (°/s)

Subjective difficulty scores. After each viewing condition, the subject was asked to rate the subjective difficulty on a scale ranging from 1 – "(almost) no problem" to 5 – "(almost) unworkable".

2.5 Procedure

Each day two subjects participated. They successively received, after the general training session (§ 2.3), all eight viewing conditions, and performed four different runs (one route per run) per viewing condition, of which the first run was a training run with feedback tones (§ 2.3) and verbal feedback. Each subject performed a total of 32 runs, in which all 32 different routes were presented. When one subject was flying a set of four runs, the other subject rested. The order in which viewing conditions were presented, as well as the order of routes was balanced across subjects; the 32 different routes were equally distributed over all eight viewing conditions (according to a Greek-Latin square design).

2.6 Statistical design

Analyses of variance were run with the package STATISTICA 5.0® ANOVA/MANOVA, with the following sub-designs from the eight viewing conditions (§ 2.1):

FOV	(windows 17° – 34° – 57°) × replica(3) × subject(8)
DISPLAY TYPE	(window 34° – tubes – HMD mono) × replica(3) × subject(8)
STEREO	(HMD mono – HMD stereo) × replica(3) × subject(8)
LAG	(no lag – lag) × (windows 17° – 57°) × replica(3) × subject(8)

The significance of main effects and interactions was tested against the factor subject. Post-hoc Tukey tests were performed for significant effects involving more than two levels.

3 RESULTS

3.1 Steering bias

One may question whether the feedback during the training runs suffices to learn to stay on a more or less invisible track. The results show that the average deviation from the perfect course was rather small: 0.11 m horizontally and 0.42 m vertically. There was no significant effect of viewing condition on this bias.

3.2 Effects of the factors FOV and of Display Type

Figures 2 a,b show results for some of the performance indicators for various FOV sizes and display types, Figures 2 c–e show some of the head motion data and Figure 2e shows the subjective difficulty ratings made by the subjects. All data are for the monocular viewing and no-lag conditions.

Performance

Generally, the data showed a significant increase in performance with increasing FOV (see Table I and Figures 2 a,b). The subjective difficulty ratings agreed very well with the objective performance indicators.

Table I Statistics for the effects of the factor **FOV** on steering performance.

Performance indicator	F(2,14)	p-level
standard deviation of the lateral error (SDH)	29.2	****
standard deviation of the lateral error speed (SDSPEEDH)	35.2	****
standard deviation of the vertical error (SDV)	15.7	**
standard deviation of the vertical error speed (SDSPEEDV)	11.3	**
**** p≤.0001; *** p≤.001; ** p≤.01; * p≤.05; ns p>.05		

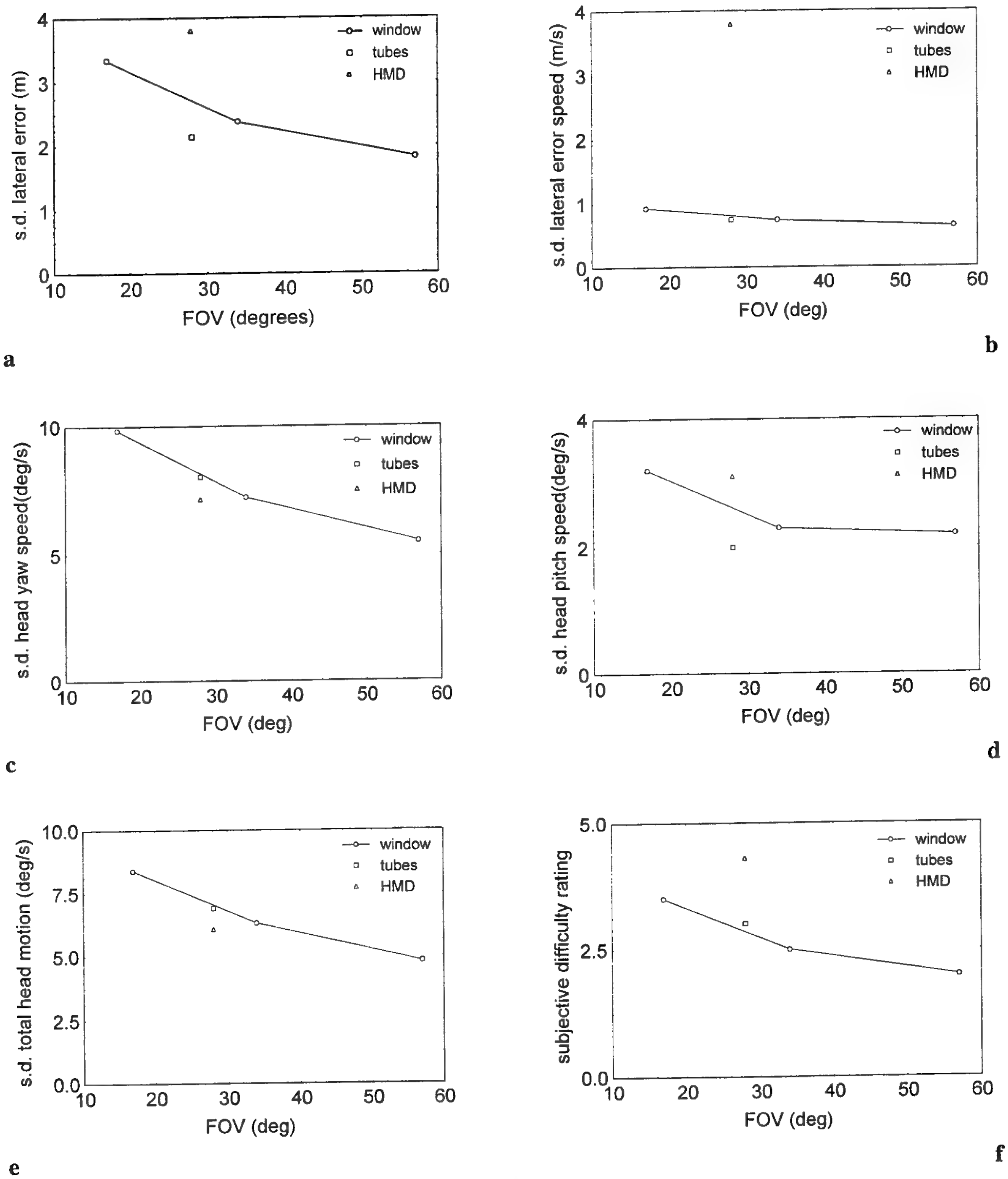

Fig. 2 A representative overview of the results for monocular viewing and without additional lag. Performance indicators (a,b), head movement data (c–e) and subjective difficulty ranking (f) as a function of FOV and display type.

Post-hoc Tukey tests showed the results for all FOV values to differ significantly from each other except in two cases, SDV for field sizes 17 and 34° and SDSPEEDV for field sizes 34 and 57°.
The data also showed a remarkable large and significant (see Table II) difference between the performance with the simulated HMD (using the window or the tube method) and the real HMD, with the simulated HMDs scoring better than the real HMD.

Table II Statistics for the effects of the factor **display type** on steering performance.

Performance indicator	F(2,14)	p-level
standard deviation of the lateral error	10.4	**
standard deviation of the lateral error speed	18.5	***
standard deviation of the vertical error	22.5	****
standard deviation of the vertical error speed	10.3	**
**** $p \leq .0001$; *** $p \leq .001$; ** $p \leq .01$; * $p \leq .05$; ns $p > .05$		

Post-hoc Tukey tests showed the real HMD to differ from both simulated HMDs for all performance indicators. The "tube HMD" and the "window HMD" did not differ significantly for any indicator.

Head movements

The FOV had a significant effect on most head movement descriptors (see Table III and Figures 2 c–e). Clearly, the subjects made less and slower movements when the FOV is large.

Table III Statistics for the effects of the factor **FOV** on head movements.

Head movement descriptor	F(2,14)	p-level
standard deviation of the yaw	22.1	****
standard deviation of the yaw speed	40.0	****
standard deviation of the pitch	0.22	ns
standard deviation of the pitch speed	8.99	**
mean total head speed	39.7	****
standard deviation of total head speed	32.2	****
**** $p \leq .0001$; *** $p \leq .001$; ** $p \leq .01$; * $p \leq .05$; ns $p > .05$		

Generally, the HMD-type did not have a significant influence on head movements. Table IV presents the results of ANOVAs which show that this factor has a significant effect on the standard deviation of the vertical head velocity only. Post-hoc Tukey tests revealed the differences between the real HMD and the simulated HMDs for this descriptor to be significant. The simulated HMDs did not differ significantly.

Table IV Statistics for the effects of the factor **Display Type** on head movements.

Head movement descriptor	F(2,14)	p-level
standard deviation of the yaw	0.24	ns
standard deviation of the yaw speed	0.86	ns
standard deviation of the pitch	0.93	ns
standard deviation of the pitch speed	14.3	***
mean total head speed	1.43	ns
standard deviation of total head speed	0.71	ns
**** $p \leq .0001$; *** $p \leq .001$; ** $p \leq .01$; * $p \leq .05$; ns $p > .05$		

Subjective difficulty

The subjective difficulty rankings supported the results on performance (compare figure1 a,b with f), in the sense that low performance was coupled with responses of high subjective difficulty.

3.3 Lag

Performance

The two extreme FOV values (17 and 57°) were used with and without an additional lag of 50 ms. Figure 3 shows the resulting performance for the standard deviation of the lateral error and the standard deviation of the lateral error speed. In both graphs the influence is clear. An ANOVA shows that the effect of lag was statistically significant for three of the four performance indicators (see Table V). Lag did not result in significant subjective difficulty rating differences.

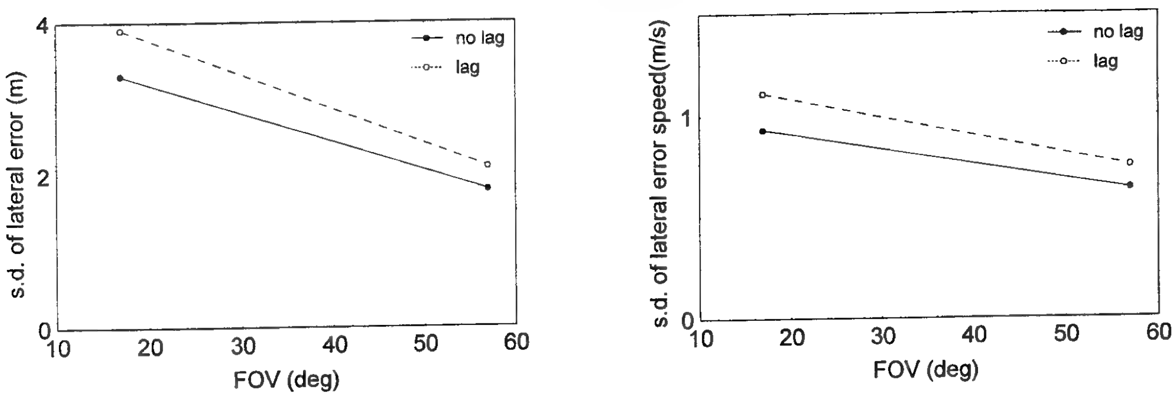

Fig. 3 Influence of lag on steering performance.

Table V Statistics for the effects of the factor **Lag** on steering performance.

Performance indicator	F(1,7)	p-level
standard deviation of the lateral error (SDH)	6.4	*
standard deviation of the lateral error speed (SDSPEEDH)	37.4	***
standard deviation of the vertical error (SDV)	25.4	**
standard deviation of the vertical error speed (SDSPEEDV)	2.8	ns
**** $p \leq .0001$; *** $p \leq .001$; ** $p \leq .01$; * $p \leq .05$; ns $p > .05$		

Head movements

The lag did not influence head movements as indicated by most of the head movement indicators, except for the s.d. of the pitch and the s.d. of the pitch speed ($F(1,7)=12.8$, $p=.009$ and $F(1,7)=6.1$, $p=.04$, respectively). In the case of the first indicator a significant interaction between FOV and lag was present ($F(1,7)=6.2$, $p=.04$); a post-hoc Tukey test indicated that only for a FOV of 57° there is a significant effect ($p=.0005$) of lag. In this case the standard deviation of the pitch was lower (2.1°) when lag is present than when no lag was added (2.8°). The s.d. of the pitch speed decreased from 2.7 °/s to 2.0 °/s when a lag was added. There was no significant interaction of FOV and lag in this case.

Subjective difficulty

Lag did not significantly influence subjective difficulty ratings.

3.4 Stereoscopic vs. monocular HMD presentation

None of the performance indicators indicated a difference between monocular and stereoscopic HMD presentation. As far as head movements are concerned, only in one case did the data show a significant effect: The average pitch in the stereo condition was 1.5° higher than in the monocular viewing condition ($F(1,7)=20.5$, $p=.003$). This was probably a spurious result. The subjective difficulty ranking did not indicate a preference for either monocular or stereoscopic presentation.

4 CONCLUSIONS AND DISCUSSION

We have measured the influence of Field Of View, image lag, monocular and stereoscopic presentation, and display type on several performance indicators, head movement descriptors and subjective difficulty ratings. Of these factors, FOV has a profound effect on the measurements, with less steering errors and less head movements with higher FOVs. The same clear results are found for the display types, with the simulated HMDs scoring noticeably better than the real HMD. The effect of lag is clear in the performance data, but not in the head movement data. There is no apparent effect of monocular or stereoscopic presentation.

Field Of View

The effects of the FOV on head movements are easily explained. For a particular FOV the movement behaviour is dictated by the course ahead (see Figure 4). The smaller the FOV the less the amount of information about the approaching course features can be acquired instantaneously and therefore more and faster head movements are necessary to collect the required information in time.

The effects of the FOV on the steering accuracy are less easily explained. In principle, all the information present in the case of a large FOV can be gathered by increasing the amount of head movements if the FOV is small. Four possible explanations for a lower performance at small FOVs are:

1 Initiating and controlling the increased amount of head movements increases the workload which interferes with the steering task. Normally, head movements are both controlled by attention (foveal selection) and by events in the outer periphery of the retina. With HMDs the FOV is too small to cover the periphery and therefore head movements need to be initiated more consciously. Furthermore, some subjects reported interference of head motion with their perception of vehicle motion.

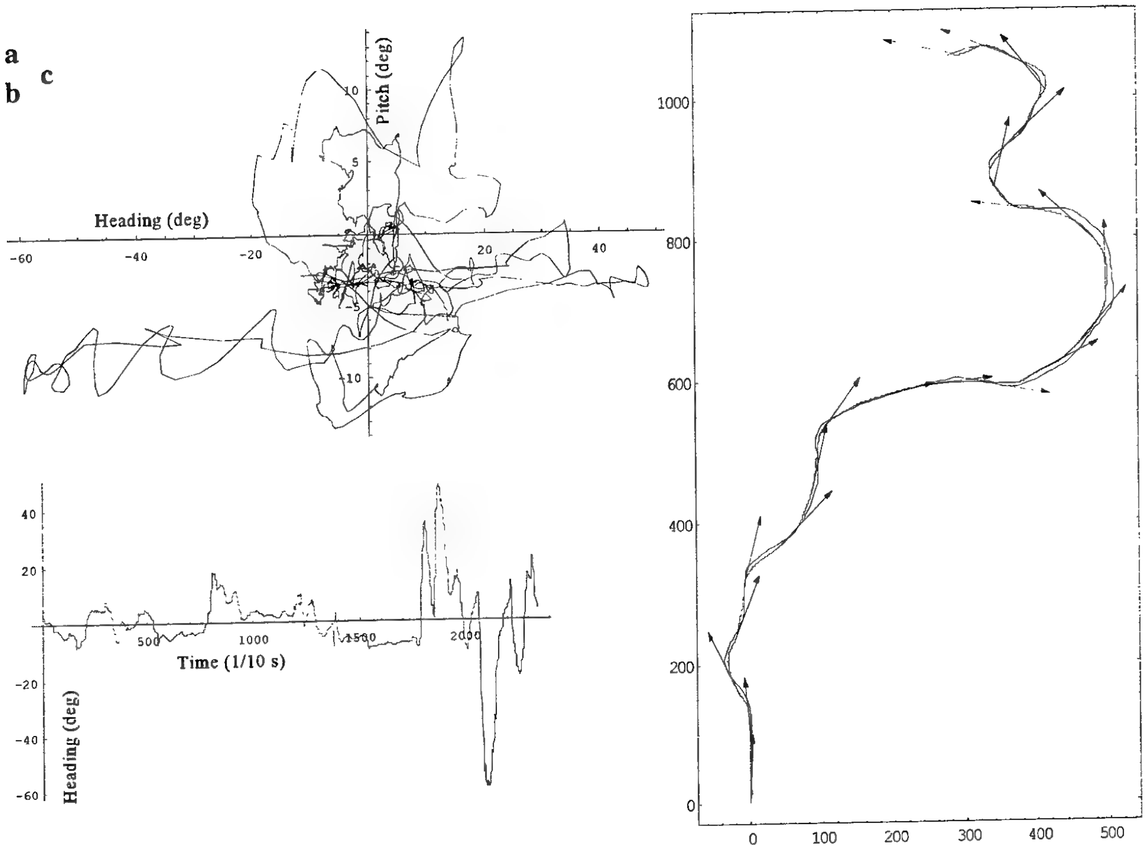

Fig. 4 A closer analysis of the head movements of a subject during a particular run using a simulated HMD with FOV of 17 degrees. Please note that the plot only indicates the head direction and not the direction of the eyes. **a:** A plot of heading and pitch directions showing a tendency to fixate in the forward direction and some rare extreme movements in either pitch and heading directions. **b:** A heading vs. time plot reveals that the heading is close to zero for most of the time except for some rapid movements at the end of the run. **c:** A plot of the actual flown track (starting point of the arrows), the ideal track and the general viewing direction (indicated by the arrows). This plot explains the sharp movements at the end of the heading-time plot. High heading values are necessary when the route is changing sharply.

2 The increased amount of head movements does not fully compensate for the loss of information content due to a smaller FOV. This hypothesis is supported by the data: the horizontal viewing angle range (here loosely defined as the range in which 95% of the head movements can be found plus the instantaneous FOV) is 59.7°, 64.6° and 76.4° for the small, mid-size and large FOV, respectively. Even if we examine the full range of head movements (extreme values) is the horizontal viewing range about 10° larger for the large FOV than for the small FOV. This is much clearer in the pitch data. The s.d. of the pitch showed no effect of FOV, which means that the subjects did not compensate for decreased vertical FOV. Compensation of decreasing vertical FOV was probably less

necessary since the largest changes in the course were in horizontal direction and not in the vertical direction.

3 The increased amplitude and velocity of the head movements decreases the accuracy with which visual data is acquired and used. It is known that head movements may lead to considerable retinal slip. However, it seems that this retinal slip does not diminish visual acuity considerably (Sperling, 1990; Steinman & Collewijn, 1980).

4 Increased head motions may lead to (subconscious) symptoms of simulator sickness. One of the subjects got sick during the experiments while using a small FOV. He was replaced by another subject who, as all the others, did not show similar symptoms. Nevertheless, a slight discomfort may play a role.

Image lag

Although our head slaving lag was rather small at 50 ms, it resulted in noticeable performance loss (about 20% higher error scores) and a small reduction in head movements (25 % less pitch standard deviation with lag, but then only in the 57° case and no significant influence on head yaw movements). Grunwald et al. (1991), using a lag of 500 ms, found a small influence on performance (4% higher error scores) but a large impact on head movements (a 53% lower head yaw rate). The differences in head movements may be explained by the lower lag value we used. The higher steering error rates we obtained may be due to the higher importance for steering accuracy of the head movements in our set up.

Monocular vs. stereoscopic presentation

Stereoscopic presentation did not improve the steering performance. This can not be explained by the fact that the subjects made head movements. Although Steinman and Collewijn (1980) show that head rotations lead to retinal slip and that vergence is not kept stable during the movements, their results and those of Patterson and Fox (1984) and others (see e.g. Regan, Frisby, Poggio, Schor & Tyler, 1990) indicate that stereo-acuity is not impaired by head movements.

Calculations of optimal just noticeable depth differences (jnd) for the Virtual IO HMD, based on its addressable resolution, show that at a distance of 3 m a depth jnd of about 9 cm could be achieved. The s.d. of the lateral error is 2-4 m, so the resolution may not seem to restrict the utility of the stereoscopic presentation. However, in course planning pilots and drivers look forward in time. Values of about 2-5 s are quite common, which in our case means looking ahead approximately 15-40 m. The jnd at these distance is 3-24 m, so it follows that stereo given the resolution of the Virtual IO HMD is probably of not much use. Furthermore, the monocular cues in the scene were quite strong; all trees were of the same size, and therefor their size in projection corresponded directly with distance. The effect of a stereo cue may have been drowned in the effects of this monocular cue.

Display type

A part of the lower performance of the real HMD as compared to the performance with simulated HMDs may be explained by the almost unnoticeable motion smear present in the HMD. This smear is due to the inertia of the LCD display. In any case, the results can not be explained by resolution differences. The addressable vertical resolution of the real HMD is *higher* by a factor of almost 2 compared to the simulated HMDs. Moreover, Van Erp (1996) showed for manoeuvring tasks that drivers tolerate a reduction of the resolution by a factor of 2 without loss of performance. To explain the results in terms of resolution would therefore imply that the VGA to NTSC conversion needed to drive the Virtual IO HMD lowers the resolution by at least a factor of 4, which would have been clearly noticeable. Since this was not the case, and because all objects in the database were rather large and visible distances short, we may exclude resolution as an explanation.

With the simulated HMDs, vergence and accommodation of the eyes match. Both are at a distance of about 3 m. For the Virtual IO HMD (Kooi, 1996), convergence is at 2.5 m and accommodation at 4 m. Accommodation is a weak cue which does not have much influence at distances over 1-2 m. Effects of convergence have a slightly larger range, but the effects of the differences between convergence of real and simulated HMDs are too small to account for the difference in performance.

We conjecture that the simulated HMDs work better because they give the subjects the possibility to orient themselves in space: the projection screen is dimly visible and its centre corresponds with the heading direction of the UAV. When using the HMD, no such visual orientation marks are present. Since the optic flow is a combination of head motion and vehicle motion and the head motion may not be accurately represented internally, estimation of the heading direction will be more difficult for a real HMD than for a simulated HMD. It suggests that users of immersive HMDs should be provided with reference marks. This hypothesis will be tested in a future experiment.

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14. **SUPPLEMENTARY NOTES**

15. **ABSTRACT (MAXIMUM 200 WORDS (1044 BYTES))**

Military use of Unmanned Aerial Vehicles (UAVs) is gaining importance. Video cameras in these devices are often operated with joysticks and their image is displayed on a CRT. In this experiment, the simulated camera of a simulated UAV was slaved to the operator's head movements and displayed using a Helmet Mounted Display (HMD). The task involved manoeuvring a UAV along a winding course marked by trees. The influence of several parameters of the set-up (HMD optics, Field of View (FOV), image lag, monocular vs. stereoscopic presentation) on a set of flight handling characteristics was assessed. To enable variation of FOV and to study the effect of the HMD optics, a simulated HMD image consisting of a head slaved window (with variable FOV), was projected on a screen. One of the FOVs, generated in this way, corresponded with the FOV of the real HMD, enabling a comparison. The results show that the simulated HMD yields a significantly better performance than the real HMD. Performance with a FOV of 17° is significantly lower than with 34 or 57°. An image lag of 50 ms, typical of pan-and-tilt servo motor systems, has a small but significant influence on steering accuracy. Monocular and stereoscopic presentation did not result in significant performance differences.

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